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Introduction

Two developments in the nineteenth and twentieth century changed the way people lived: the automobile and telecommunications. Prior to the widespread availability of personal automobiles, individuals had to travel on foot, by bicycle, or on horseback. Trains provided faster travel between cities, but most people's lives were centered on their home town and immediate surroundings. A journey of 100 miles was a major expedition for most people, and the easy mobility that we all take for granted in the twenty-first century was unknown. Before the telegraph and telephone came into widespread use, all communication was face to face, or in writing. If you wanted to talk to someone, you had to travel to meet with that person, and travel was slow and arduous. If you wanted to send information, it had to be written down and the papers hand-carried to their destination.

Telecommunication systems have now made it possible to communicate with virtually anyone at any time. Early telegraph and telephone systems used copper wire to carry signals over the earth's surface and across oceans, and high frequency (HF) radio made possible intercontinental telephone links.

The development and installation of optical fibers and optical transmission techniques has greatly increased the capacity of terrestrial and oceanic links. Artificial earth satellites have been used in communications systems for more than 50 years and have become an essential part of the world's telecommunications infrastructure. Satellites allow people to receive hundreds of television channels in their homes, either by receiving direct broadcast satellite television signals, or via cable TV from a satellite distribution center. Virtually all cable TV systems collect their signals from satellites that distribute television programming nationwide. Access to the internet via satellite from areas that are not served by cable is also available, providing many people in rural areas with much faster service than can be achieved over telephone lines.

1.1 Background

The origins of satellite communications can be traced to an article written by Arthur C. Clarke in the British radio magazine *Wireless World* in 1945 (Clarke 1945). At the time, Clarke was serving in the British Royal Air Force, working on precision approach radar systems that could guide World War II aircraft to a safe landing when the airport was fogged in. He was interested in long distance radio communication and was among the first to propose a practical way to communicate using satellites. He later became

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famous as the author of *2001: A Space Odyssey*, and other science fiction books (Clarke 1968). In 1945, HF radio was the only available method for radio communication over transcontinental distances, and it was not at all reliable. Sun spots and ionospheric disturbances could disrupt HF radio links for days at a time. Telegraph cables had been laid across the oceans as early as the mid-1800s, but cables capable of carrying voice signals across the Atlantic did not begin service until 1953. Clarke suggested that a radio relay satellite in an equatorial orbit with a period of one sidereal day would remain stationary with respect to the earth's surface and make possible long distance radio links. (A sidereal day is the time it takes for the earth to make one complete revolution on its axis. It is 3 minutes 55.91 seconds shorter than a clock day of 24 hours, accounting for the progress of the earth around the sun in 365 days, which adds one additional revolution.)

Clarke's *Wireless World* paper is available on the internet and makes fascinating reading (Clarke 1945). Solar arrays had not been developed in 1945, so Clarke proposed a solar collector driving a steam engine to generate electrical power; a manned space station was needed to run the complicated systems. In most other respects, Clarke accurately predicted the development of geostationary earth orbit (GEO) satellites for direct broadcast television and data communications using transmitter powers much lower than the kilowatt levels of terrestrial broadcasting, and small parabolic mirrors (dishes) for receiving terminals.

At the time Clarke wrote his paper there were no satellites in orbit nor rockets powerful enough to launch them. But his ideas for what we now know as a geostationary satellite system were not science fiction, as the launch of the Russian satellite *Sputnik* in 1957 and subsequent GEO satellites was to prove. In 1965 the first geostationary communications satellite, *Early Bird*, began to provide telephone service across the Atlantic Ocean, fulfilling Clarke's vision of 20 years earlier. Intelsat launched a series of satellites between 1967 and 1969 that provided coverage of the Atlantic, Pacific, and Indian ocean regions, making worldwide coverage by GEO satellite possible, just in time for the Apollo 11 mission that first sent humans to the moon.

Satellite communication systems were originally developed to provide long distance telephone service. In the late 1960s, launch vehicles had been developed that could place a 500 kg satellite in geostationary earth orbit, with a capacity of 5000 telephone circuits, marking the start of an era of expansion for telecommunication satellites. Geostationary satellites were soon carrying transoceanic and transcontinental telephone calls. For the first time, live television links could be established across the Atlantic and Pacific oceans to carry news and sporting events. From its early beginnings in the 1960s, revenue earned from satellite communication systems has increased at an average of about 5% every year, and was valued at US$260B in 2016. Growth was rapid in the early 2000s, falling to 2% by 2016 (SIA 2017).

By year 2016, there were a total of 1459 active satellites in orbit with over 500 GEO communication satellites serving every part of the globe. Although television accounts for much of the traffic carried by these satellites, international and regional telephony, data transmission, and internet access are also important. In the populated parts of the world, the geostationary orbit is filled with satellites every two or three degrees, operating in almost every available frequency band. The global positioning system (GPS) uses 24 satellites in medium earth orbit (MEO) to provide worldwide navigation data for automobiles, ships, and aircraft. The worldwide revenue from Global Navigation Satellite Systems (GNSS) installations, mainly in automobiles, was US$74B in 2016 (SIA 2017).

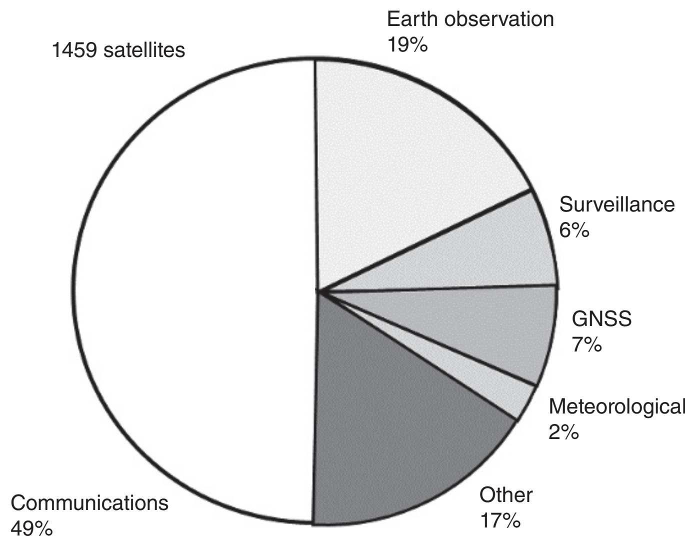

Figure 1.1 Distribution of satellites in orbit in 2016 by application. More than 500 satellites were in geostationary orbit. Communications includes DBS-TV, civil, and military links. Earth observation by small satellites increased quickly between 2014 and 2017 with the introduction of cubesats. Source: Adapted from data in (SIA 2017).

Figure 1.1 shows how the 1459 active satellites in orbit in 2016 were divided by application. Direct broadcast satellite television (DBS-TV) and video distribution services were the dominant uses of satellites, while navigation services made a major contribution. The large number of earth observation satellites were mainly cubesats.

Figure 1.2 shows the distribution of revenues generated by the worldwide satellite industry, divided by application. As in Figure 1.1, DBS-TV and video distribution generate more than half the revenue.

GEO satellites have grown steadily in mass, size, lifetime, and cost over the years. Some of the largest satellites launched to date are the KH and Lacrosse surveillance satellites of the US National Reconnaissance Office weighing an estimated 13 600 kg (30 000 lb) (KH-11_Kennen 2017). By 2000, commercial telecommunications satellites weighing 6000 kg with lifetimes of 15 years were being launched into geostationary orbit at a typical cost around US$125M for the satellite and launch. These costs did not change greatly over the following 15 years, although larger satellites with much higher capacity, and higher cost, have also been launched since 2011. The revenue earning capacity of a GEO satellite costing US$125M in orbit must exceed US$20M per year for the venture to be profitable, and must compete with optical fibers in carrying voice, data, and video signals. A single optical fiber can carry 10 Gbps at a single wavelength of light, and 100 Gbps by employing multiple wavelengths, a capacity similar to that of the largest GEO satellites, and optical fibers are never laid singly but always in bundles. The latest trans-Pacific optical fiber cable can transport 60 terabits per second using multiple optical fibers and optical wavelengths, equivalent to the capacity of 50 large GEO satellites in 2018 (The Verge 2017). GEO satellites cannot compete with optical fibers for point to point communications, but have the advantage of broadcasting to millions of receiving terminals simultaneously. Any place within the satellite coverage can be served by simply installing an earth terminal. To do the same with a fiber optic link requires fiber

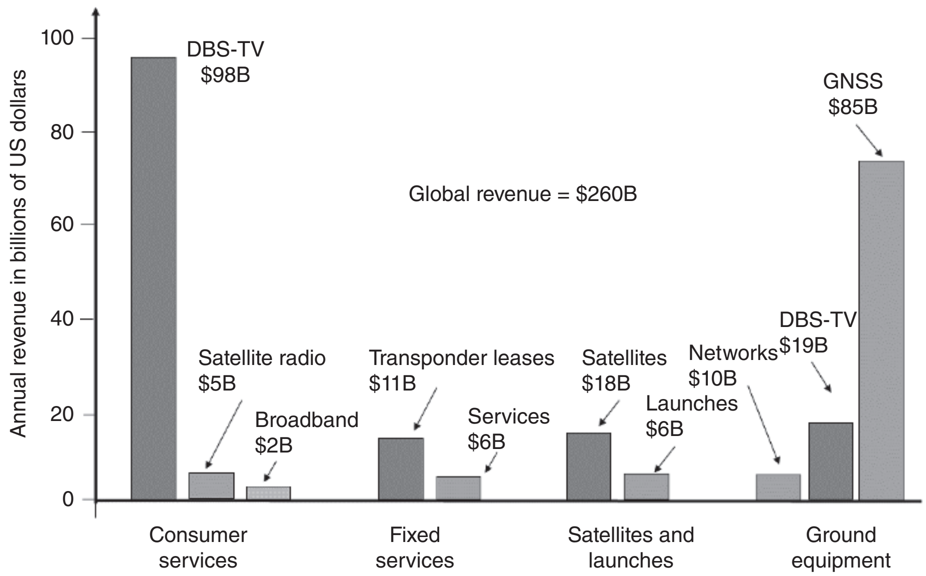

Figure 1.2 Distribution of global revenue earned from all satellite activity in 2016. Direct broadcast satellite television (DBS-TV) and Global Navigation Satellite Systems (GNSS) dominate with US$183B in revenue out of a total of US$261B. Source: Adapted from data in (SIA 2017).

to be laid. Fiber optic transmission systems dominate where there is a requirement for high capacity point-to-point links; GEO satellites succeed best when broadcasting.

> The high capacity of both optical fibers and satellites, and the steady move of telecommunications traffic from analog signals to digital has lowered the cost of long distance telephone calls and increased enormously the number of circuits available. In 1960, prior to the advent of satellite communications, the United States had 550 overseas telephone circuits. Calls to Europe cost more than US$1.00 per minute at 1960 prices, and had to be placed through an operator, with delays of many hours being common. By 2016, virtually all international calls could be dialed by the end user, and rates to Europe had dropped to below US$0.02 per minute. To put the reduction in the cost of an international telephone call in perspective, we must remember that incomes have risen significantly over this time period. In the 1950s, the average wage in the United States was US$2.10 per hour, so the average worker would have had to work for 30 minutes to pay for a one minute call to Europe. In 2017, the average wage in the United States was US$26.10 per hour, and required less than 10 second's earnings to pay for the same international call. The United States now has hundreds of thousands of overseas telephone circuits, and video links daily carry live news reports from all over the globe. Texts and emails can be sent over the internet anywhere in the world for free. Telecommunications and computers lowered costs by a factor approaching 2000 between 1960 and 2010, something no other sector of the economy has ever achieved. The electrical and computer engineers who have made this possible rarely get the credit from the general public that they deserve.

GEO satellites have been supplemented by low and medium earth orbit satellites for some applications. Low earth orbit (LEO) satellites can provide satellite telephone and data services over continents or the entire world, and are also used for earth imaging and surveillance. The delay incurred in a telephone link via a LEO satellite is much lower than with a GEO satellite, but because LEO satellites travel across the sky complicated handoff procedures are needed to ensure continuous communication. The dominance of GEO satellites for internet access by satellite will be challenged after 2020 as the proposed 12 000 LEO satellites operating in Ku-, Ka-, and V-band begin to provide worldwide access to the internet.

The global positioning system uses 24 medium earth orbit satellites to broadcast signals to the entire earth's surface. GPS, and Galileo, a similar European position location system have revolutionized navigation by vehicles, ships and aircraft, and GPS receivers have become a consumer product. Every cellular telephone has a GPS receiver built into it and cars are now available with built-in GPS receivers so that drivers should not get lost. Emergency calls from cellular phones carry information about the phone's location based on received GPS data.

1.2 A Brief History of Satellite Communications

Satellite communications began in October 1957 with the launch by the USSR of a small satellite called *Sputnik I*. This was the first artificial earth satellite, and it sparked the space race between the United States and the USSR. Sputnik I carried only a beacon transmitter and did not have communications capability, but demonstrated that satellites could be placed in orbit by powerful rockets. The first satellite successfully launched by the United States was Explorer I, launched from Cape Canaveral on 31 January 1958 on a Juno I rocket. The first voice heard from space was that of President Eisenhower, who recorded a brief Christmas message that was transmitted back to earth from the Project Score satellite in December 1958. The Score satellite was essentially the core of the Atlas intercontinental ballistic missile (ICBM) booster with a small payload in the nose. A tape recorder on Score had a storage capacity that allowed a four-minute message received from an earth station to be retransmitted. The batteries on Score failed after 35 days in orbit.

After some early attempts to use large balloons (Echo I and II) as passive reflectors for communication signals, and some small experimental satellite launches, the first true communications satellites, Telstar I and II, were launched in July 1962 and May 1963. The Telstar satellites were built by Bell Telephone Laboratories and used transponders adapted from terrestrial microwave link equipment. The uplink was at 6389 MHz and the downlink at 4169 MHz, with 50 MHz bandwidth. The satellites carried solar cells and batteries that allowed continuous use of the single transponder, and demonstrations of live television links and multiplexed telephone circuits were made across the Atlantic Ocean, emphatically demonstrating the feasibility of satellite communications.

The Telstar satellites were launched into what is now called a medium earth orbit, with periods of 158 and 225 minutes. This allowed transatlantic links to operate for about 20 minutes while the satellite was mutually visible. The orbits chosen for the Telstar satellites took them through several bands of high energy radiation, which caused early failure of the electronics on board. However, the value of communication satellites had been demonstrated and work was begun to develop launch vehicles that could deliver a payload to geostationary orbit, and to develop satellites that could provide useful communication capacity (Telstar 2018).

On 24 July 1961, US President John F. Kennedy defined the general guidelines of US policy in regard to satellite communications and made the first unambiguous references to a single worldwide system. On 20 December 1961, the US Congress recommended that the International Telecommunications Union (ITU) should examine the aspects of space communications for which international cooperation would be necessary. The most critical step was on 20 December 1961, when the US Congress passed the Communications Satellite Act. This set the stage for commercial investment in an international satellite organization and, on 19 July 1964, representatives of the first 12 countries to invest in what became Intelsat (the International Telecommunications Satellite Organization) signed an initial agreement. The company that represented the United States at this initial signing ceremony was Comsat, an entity Congress created to act for the United States within Intelsat. At this point the Bell System had a complete monopoly of all long distance telephone communications within the United States. When Congress passed the Communications Satellite Act, the Bell System was specifically barred from directly participating in satellite communications, although it was permitted to invest in Comsat.

Comsat essentially managed Intelsat in the formative years and should be credited with the remarkable success of the international venture. The first five Intelsat series of satellites (INTELSAT I through V) were selected, and their procurement managed, by teams put in place under Comsat leadership. Over this same phase, though, large portions of the Comsat engineering and operations groups transferred over to Intelsat so that, when the Permanent Management Arrangements came into force in 1979, many former Comsat groups were now part of Intelsat. Intelsat was eventually sold to private investors in 2001, and the proceeds divided up among the member counties. Intelsat was sold for US$3.1B in January 2005 to four private equity firms. The company acquired PanAmSat on 3 July 2006, and is now the world's largest provider of fixed satellite services, operating a fleet of 52 GEO satellites. In June 2007 BC Partners announced they had acquired 76% of Intelsat for about 3.75 billion euros (Intelsat 2017). (Fixed satellite services provide communications between earth stations that do not move, in contrast to mobile satellite services.)

In mid-1963, 99% of all satellites had been launched into LEO, and the higher MEO were much easier to reach than GEO with the small launchers available at that time. The intense debate was eventually settled on launcher reliability issues rather than on payload capabilities. The first six years of the so-called space age was a period of both payload and launcher development. The new frontier was very risky, with about one launch in four being fully successful. The system architecture of the first proposed commercial communications satellite system employed 12 satellites in an equatorial MEO constellation. Thus, with the launch failure rate at the time, 48 launches were envisioned to guarantee 12 operational satellites in orbit. Without 12 satellites in orbit, continuous 24-hour coverage could not be offered. Twenty-four hours a day, seven days a week – referred to as 24/7 operation – is a requirement for any successful communications service. A GEO systems architecture requires only one satellite to provide 24/7 operation over essentially one third of the inhabited world. On this basis, four launches would be required to achieve coverage of one third of the earth; 12 for the entire inhabited world. Despite its unproven technological approach, the geostationary orbit was selected by the entities that became Intelsat.

Launching satellites has become more reliable, with the best performance achieved by the United Launch Alliance (ULA) formed by Boeing and Lockheed-Martin. By 2016

ULA had conducted 164 consecutive satellite launches without a single failure. Newer entrants to the launch business offering much lower cost launches than ULA have been less successful, with occasional spectacular launch failures when the rocket exploded on the launch pad.

The first Intelsat satellite, INTELSAT I (formerly Early Bird) was launched on 16 April 1965. The satellite weighed a mere 36 kg (80 lb.) and incorporated two 6/4 GHz transponders, each with 25 MHz bandwidth. Commercial operations commenced between Europe and the United States on 28 June 28 1965. Thus, about two decades after Clarke's landmark article in *Wireless World*, GEO satellite communications began. Intelsat was highly successful and grew rapidly as many countries saw the value of improved telecommunications, not just internationally but for national systems that provided high quality satellite communications within the borders of large countries.

Canada was the first country to build a national telecommunication system using GEO satellites. ANIK 1A was launched in May 1974, just two months before the first US domestic satellite, WESTAR 1. The honor of the first regional satellite system, however, goes to the USSR Molniya system of highly elliptic orbit (HEO) satellites, the first of which was launched in April 1965 (the same month as INTELSAT I). Countries that are geographically spread like the former USSR, which covered 11 time zones, have used regional satellite systems very effectively. Another country that benefited greatly from a GEO regional system was Indonesia, which consists of more than 3000 islands spread out over more than a thousand miles. A terrestrially based telecommunication system was not economically feasible for these countries, while a single GEO satellite allowed instant communications region wide. Such ease of communications via GEO satellites proved to be very profitable. Within less than 10 years, Intelsat was self-supporting and, since it was not allowed to make a profit, it began returning substantial revenues to its Signatories. Within 25 years, Intelsat had more than 100 Signatories and, in early 2000, there were 143 member countries and Signatories that formed part of the international Intelsat community (Intelsat 2017).

The astonishing commercial success of Intelsat led many nations to invest in their own satellite systems, and by 2015 a total of 57 countries were operating one or more active satellites. Many of the original Intelsat Signatories had been privatized by the early 1990s and were, in effect, competing not only with each other in space communications, but with Intelsat. It was clear that some mechanism had to be found whereby Intelsat could be turned into a for-profit, private entity, which could then compete with other commercial organizations while still safeguarding the interests of the smaller nations that had come to depend upon the remarkably low cost communications cost that Intelsat offered. The first step in the move to privatizing Intelsat was the establishment of a commercial company called New Skies and the transfer of a number of Intelsat satellites to New Skies.

In the 1970s and 1980s there was rapid development of GEO satellite systems for international, regional, and domestic telephone traffic and video distribution. In the United States, the expansion of fiber optic links with very high capacity and low delay caused virtually all telephone traffic to move to terrestrial circuits by 1985. However, the demand for satellite systems grew steadily through this period, and the available spectrum in the 6/4 GHz band (C-band) was quickly occupied, leading to expansion into 14/11 GHz band (Ku-band). In the United States, most of the expansion after 1985 was in the areas of video distribution and very small aperture terminals (VSAT) networks. By 1995 it was clear that the GEO orbit capacity at Ku-band would soon be filled, and 30/20 GHz

(Ka-band) satellite systems would be needed to handle the expansion of digital traffic, especially wide band delivery of high speed internet data. Société Européenne de Satellites (SES), based in Luxemburg, began two way multimedia and internet access service in western and central Europe at Ka-band using the Astra 1H satellite in 2001 (SES Astra 2001). Direct to home satellite TV (DHS-TV), also called direct broadcast satellite TV continued to grow its customer base in the United States until 2016 when demand leveled off as subscription TV services became available on the internet.

In 2011 ViaSat launched ViaSat I, a Ka-band satellite with a digital data capacity of 140 Gbps, exceeding the combined capacity of all the Ku-band digital data satellites in orbit at that time (ViaSat I 2012). ViaSat 1 has 72 spot beams, 63 over the United States and 9 over Canada, and 56 Ka-band transponders. ViaSat 1 is intended to provide direct to home internet access, using a system marketed by Echostar as *Exede,* (later called *ViaSat)* over the populated areas of the United States and Canada. Part of the Rocky Mountain region has no spot beams because of low population density, and the Canadian beams are along the country's southern border with the United States. The satellite can also be used for DBS-TV. A similar satellite called Jupiter, later named Echostar 17, was launched by HughesNet for their internet access service. HughesNet became a subsidiary of EchoStar in 2011. The high capacity satellites provide internet access with downlink speeds up to 25 Mbps and uplinks at 3 Mbps, comparable to terrestrial cable speeds. More details of internet access by satellite can be found in Chapter 11.

The ability of satellite systems to provide communication with mobile users had long been recognized, and the International Maritime Satellite Organization (Inmarsat) has provided service to ships and aircraft for several decades, although at a high price. LEO satellites were seen as one way to create a satellite telephone system with worldwide coverage; numerous proposals were floated in the 1990s, with three LEO systems eventually reaching completion by 2000 (Iridium, Globalstar, and Orbcomm). The implementation of a LEO and MEO satellite system for mobile communication has proved much more costly than anticipated, and the capacity of the systems is relatively small compared to GEO satellite systems, leading to a higher cost per transmitted bit. Satellite telephone systems were unable to compete with cellular telephone because of the high cost and relatively low capacity of the space segment. The Iridium system, for example, cost over US$5B to implement, but provided a total capacity for the United States of fewer than 10 000 telephone circuits. Iridium Inc. declared bankruptcy in early 2000, having failed to establish a sufficiently large customer base to make the venture commercially viable. The entire Iridium system was sold to Iridium Satellite LLC for a reported US$25M, approximately 0.5% of the system's construction cost.

Satellite navigation systems, known generically as GNSS have revolutionized navigation and surveying. The global positioning system, created by the US Department of Defense (DoD) took almost 20 years to design and fully implement, at a cost of US$12B. By 2000, GPS receivers could be built in Original Equipment Manufacturer (OEM) form for less than US$25, and the worldwide GPS industry was earning billions of dollars from equipment sales and services. In the United States, aircraft navigation is transitioning to a GPS based system known as Automatic Dependent Surveillance Broadcast (ADS-B), which requires all aircraft operating under air traffic control to carry ADS-B equipment by 2020. ADS-B will replace radar as the main information source for air traffic control, although some radars will be retained for air defense and detection of aircraft without ADS-B capability. ADS-B transponders on Iridium satellites will eventually provide worldwide location of all commercial aircraft. Accurate navigation of ships, especially in coastal waters and bad weather, is also heavily reliant on GPS. Europe has a comparable satellite navigation system called Galileo and China is building the Beidou system. GPS and ADS-B are the topics of Chapter 12.

1.3 Satellite Communications in 2018

Satellites come in many shapes and sizes. The smallest are cubesats, a low cost satellite that has a standard form called 1 U that is a 0.1 m cube with a maximum weight of 1 kg. Cubes can be joined together in one plane to make 2 U, 3 U … satellites. Cubes come with solar cells, batteries and options for microprocessors, plus standard software. The builder can add scientific experiments, communication systems and antennas, and other extras. Cubesats have proved popular with schools and universities because the basic satellite can be purchased for US$50 000 and a launch as a secondary payload can cost US$100 000 or less. Their development has at led to new ways of building satellites at much lower cost than large GEO satellites, and has spurred the creation of constellations of thousands of LEO satellites that can provide the entire world with internet access. Rockets that have payload space and weight to spare sometimes launch dozens of cubesats into low earth orbit (LEO). Chapter 8 discusses cubesats in more detail and Chapter 11 discusses large LEO satellite constellations.

GEO satellites were the backbone of the commercial satellite communications industry for 50 years. Large GEO satellites can serve one third of the earth's surface and can carry up to 140 Gbps of data, or transmit up to 200 high power DBS-TV signals. The weight and power of GEO satellites has increased. In 2018 a large GEO satellite could weigh 6000 kg (6 tons), generate 16 kW of power and carry 72 transponders, with a trend toward even higher powers but lower weight. Electrical propulsion systems for raising the satellite to GEO orbit and positioning over the satellite's lifetime avoid the need to carry fuel for gas jets; in a large GEO satellite fuel can account for half the initial weight of the satellite when it reaches orbit. Multiple beam antennas allow radio frequencies to be reused many times over, and also to transmit local TV channels from DBS-TV satellites. In between tiny cubesats and large GEO satellites is a range of satellites of medium size and weight that are used for earth observation and meteorology, scientific research, and communications using constellations of LEO or MEO satellites. The one common feature of all these satellites is that they require radio communication systems, the subject of this book.

Television program distribution and DBS-TV have become the major source of revenue for commercial satellite system operators, earning US$98B of the industry's US$122B revenues from communication services in 2016. By 2016 there were over 33 million DBS-TV customers in the United States and 230 million worldwide (SIA 2017). Direct to home satellite television and the distribution of video material to cable TV operators and broadcast stations has become the largest part by far of the satellite communication industry, at least until 2020. The next largest segment is position location systems, where almost all revenue comes from receiving equipment.

To achieve high capacity with a GEO satellite requires the use of high power terrestrial transmitters and high gain earth station antennas. Earth station antenna gain translates directly into communication capacity, and therefore into revenue. Increased capacity lowers the delivery cost per bit for a customer. Systems with fixed directional antennas can deliver bits at a significantly low cost than systems using low gain antennas, such as those used on mobile terminals. Until the large LEO constellations for internet access come into use, GEO communications satellites will continue to be the largest revenue earners in space, along with the consumer GPS industry that supplies GPS chips and software for automobiles and cell phones.

Low earth orbit satellites are used for surveillance of the earth's surface. Civil uses, termed earth observation, include agricultural surveys to monitor growing crops, production of maps, weather observation, and surveys of archeological sites. Visible and infrared wavelengths yield different information, especially with vegetation. The resolution of commercially available earth observation data in 2017 was about 0.3 m. Military surveillance satellites have become an important part of the defensive capabilities of many countries, and are among the largest and heaviest satellites launched to date. These satellites are in very low earth orbits to obtain the highest possible resolution, and utilize visible and infrared wavelengths as well as radar observations. Infrared emissions have the advantage of being available during the night, whereas visible observations can only be made in daylight. The resolution achieved by military satellites is classified, but is undoubtedly much higher than that of civil earth observation satellites. In 2016 several proposals were approved by the US Federal Communications Commission (US FCC) for constellations of thousands of LEO satellites in low and very low earth orbit. These satellites operate in the Ka- and V-bands (18–50 GHz) providing internet access for homes anywhere in the world, especially in counties that lack a well developed terrestrial communication system. Once completed, these constellations will have many more satellites than all the satellites previously launched into orbit.

All radio systems require frequency spectrum, and the delivery of high speed data requires a wide bandwidth. Satellite communication systems started in C-band, with an allocation of 500 MHz, shared with terrestrial microwave links. As the GEO orbit filled up with satellites operating at C-band, satellites were built for the next available frequency band, Ku-band. Both C-band and Ku-band frequency allocations have been expanded over the years to increase the capacity of the GEO orbit, both by moving other services out of the satellite band, or adopting frequency sharing techniques.

There is a continuing demand for ever more spectrum to allow satellites to expand DBS-TV offerings and to provide new services, resulting in a move to Ka-band and even higher frequencies. Access to the internet from small transmitting Ka-band earth stations located at the home offers an alternative to terrestrial cable and telephone networks, especially in rural areas. SES began two way Ka-band internet access in Europe in 1998 with the Astra-K satellite, and ViaSat and Hughes Network Systems offer internet access through their *Exede* and *Hughesnet* systems in the United States, both now owned by Echostar (2017). Worldwide access to the internet via LEO and MEO satellite systems using Ka- and V-bands is also being developed.

Successive World Radio Conferences have allocated new frequency bands for commercial satellite services that now include L, S, C, Ku, K, Ka, V, and W bands. Table 1.1 gives the frequency designations for these letter bands. Letter bands were first used in World War II to obscure the frequencies of newly developed radars. By the end of the war there were seven different letter systems in use, and at least four systems covering radio communications, radar, and electronic warfare are still in widespread use. The frequency designations for letter bands for radio communication were eventually standardized by the IEEE (IEEE Std 521-2002 2012). Mobile satellite systems use very high frequency (VHF), ultra high frequency (UHF), L- and S-bands with carrier frequencies from 137 to 2500 MHz; GEO and LEO satellites use frequency bands extending from

Table 1.1 IEEE standard definitions for radio frequency bands [IEEE Std 521-2002]

Letter band	Frequency range
HF	3–30 MHz
VHF	30–300 MHz
UHF	300 MHz–1 GHz
L	1–2 GHz
S	2–4 GHz
C	4–8 GHz
X	8–12 GHz
Ku	12–18 GHz
K	18–27 GHz
Ka	27–40 GHz
V	40–75 GHz
W	75–110 GHz
mm wave	110–300 GHz

3.2 to 50 GHz. (VHF and UHF bands are defined by the ITU, along with super high frequency (SHF) and extremely high frequency (EHF), using the adjectives very high, ultra high, super high, and extra high, in decades of frequency. These designations are rarely used above 1 GHz, except by the ITU.)

Despite the growth of fiber optic links with very high capacity, the demand for satellite systems continues to increase. Satellites have also become integrated into complex communications architectures that use each element of the network to its best advantage. Examples are very small aperture terminals/wireless local loop (VSAT/WLL) in countries where the communications infrastructure is not yet mature and Local Multipoint Distribution Systems (GEO/LMDS) for the urban fringes of developed nations where the build-out of fiber has yet to be an economic proposition.

1.4 Overview of Satellite Communications

Satellite communication systems exist because the earth is a sphere. Radio waves travel in straight lines at the microwave frequencies used for wideband communications, so a repeater is needed to convey signals over long distances. Satellites, because they can link places on the earth that are thousands of miles apart are a good place to locate repeaters. A radio frequency repeater is simply a receiver linked to a transmitter, using different radio frequencies for transmit and receive, which can receive a signal from one earth station, amplify it, and retransmit it to another earth station. The repeater derives its name from nineteenth-century telegraph links, which had a maximum length of about 50 miles. Telegraph repeater stations were required every 50 miles in a long distance link so that the Morse code signals could be resent before they became too weak to read. Repeaters on satellites are called transponders.

In 2018, the majority of communication satellites were in geostationary earth orbit, at an altitude of 35 786 km, over the equator. A typical path length from an earth station to a GEO satellite is 38 500 km. Because radio signals get weaker in proportion to the square of the distance traveled, signals reaching a satellite are always very weak. Similarly, signals received on earth from a satellite 38 500 km away are also very weak, because there are limits on the size of the antennas on GEO satellites and the electrical power they can generate using solar cells. The cost to place a geostationary satellite into orbit has fallen over the years as the number of launching options has increased. In 2018, the cost to launch a 8300 kg satellite into GEO varied from US$7600 to US$25 000 per kilogram, and a minimum of US$2700 per kilogram into LEO (Launch cost 2018). This obviously places severe restrictions on the size and weight of GEO satellites, since the high cost of building and launching a satellite must be recovered over a 10 to 15 year lifetime by selling communications capacity. LEO and MEO satellites cost less to launch, but an entire constellation of 12 to 66 satellites is needed to provide continuous coverage. In 2018 there were 160 proposals for LEO satellite systems for internet access using constellations as large as 12 000 satellites. Not all of these proposals will become working systems (Sweeting 2017).

Figure 1.3 illustrates some of the ways that satellites are used to provide communication services. In Figure 1.3a, a one way link is established between two earth stations via a single transponder on a GEO satellite. This configuration is used for the analysis of a satellite link, but not often in practice because two way communication is usually required. The transmission from earth station A to the satellite is called the uplink, and the transmission from the satellite to earth station B is called the downlink. In Figure 1.3b, the one way transmission is received by many receiving earth stations, sometimes as many as 30 million as in a DBS-TV system. DBS-TV satellites carry many transponders so that a large variety of video and audio channels can be sent to subscribers. In Figure 1.3c, a two way link is established through a single transponder. Earth station A transmits to the satellite at a frequency $f1$, which is transposed to a different frequency $f2$ by the transponder, so earth station B receives at a frequency $f2$. Earth station B transmits to the satellite at a frequency $f3$, which occupies a different part of the transponder bandwidth from earth station A's transmission at frequency $f1$. Earth station A receives signals from the satellite at a frequency $f4$. Using radio frequency to separate signals is known as frequency division multiplexing. An alternative technique is time division multiplexing, in which all transmitting stations share the same uplink frequency but transmit at different times such that their signals arrive at the satellite in sequence. All the receiving earth stations receive all the transmitted uplink signals and use time division techniques to extract the wanted signals.

Figure 1.3d illustrates a position location system such as GPS. GPS employs a constellation of 24 MEO satellites such that four satellites are always visible to a GPS receiver. The receiver compares the time of arrival of a spread spectrum sequence from each satellite and calculates the location of the receiver, and also the exact time referenced to atomic clocks on GPS satellites. All GPS receivers know time within one microsecond, which allows systems such a cellular telephones to be synchronized with great accuracy. Because a GPS receiver must simultaneously accept signals from different parts of the sky, an omnidirectional antenna is needed. Compared to the dish antennas used in DBS-TV, an omnidirectional antenna has a very low gain, so GPS signals are extremely weak.

Satellite communication systems are dominated by the need to receive very weak signals. In the early days, very large receiving antennas with diameters up to 30 m were needed to collect sufficient signal power to drive video signals or multiplexed telephone

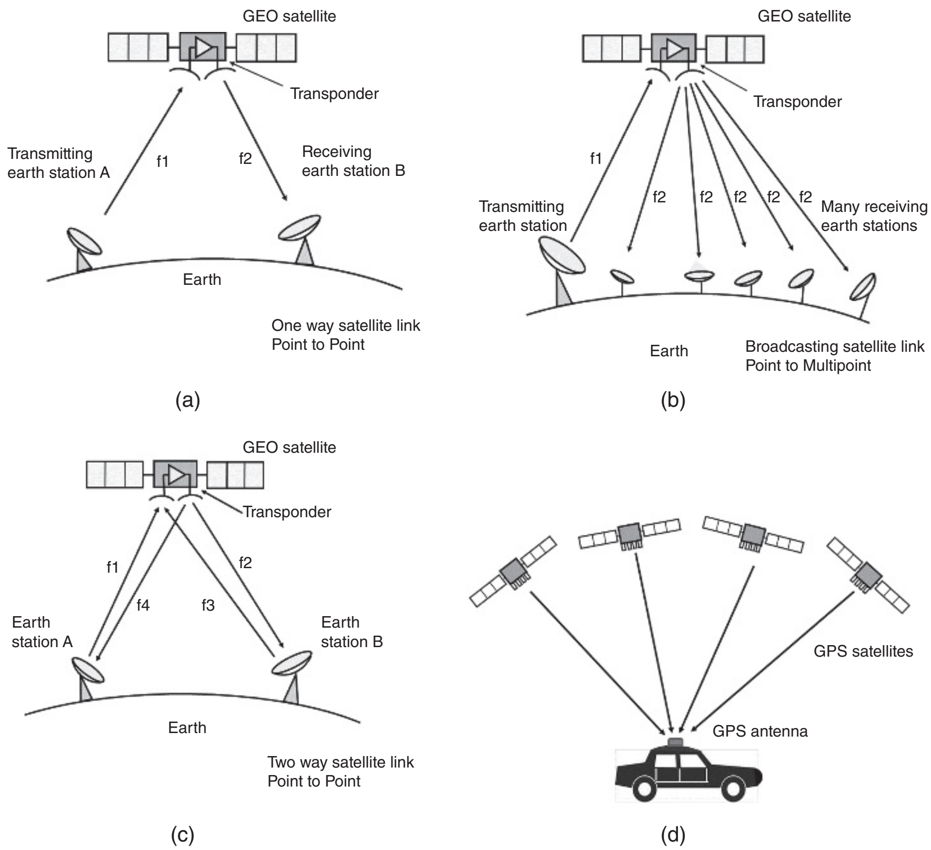

Figure 1.3 Illustration of different application of satellites. (a) One way satellite link from earth station A to earth station B. Uplink frequency is $f1$, downlink frequency is $f2$. (b) Point to multipoint link (broadcasting) from a single uplink transmitting station to many receiving stations. Uplink frequency is $f1$ and all downlinks are at the same frequency $f2$. (c) Two way connection between earth station A and earth station B. Station A transmits at frequency $f1$ and receives at frequency $f4$. Station B transmits at frequency $f3$ and receives at frequency $f2$. (d) Illustration of four GPS satellites broadcasting to an automobile. The GPS receiver uses an omnidirectional antenna.

channels. As satellites have become larger, heavier, and more powerful, smaller earth station antennas have become feasible, and DBS-TV receiving systems can use dish antennas as small as 0.5 m in diameter. Satellite systems operate in the microwave and millimeter wave frequency bands, using frequencies between 1 and 50 GHz. Above 10 GHz, rain causes significant attenuation of the signal and the probability that rain will occur in the path between the satellite and an earth station must be factored into the system design. Above 20 GHz, attenuation in heavy rain (usually associated with thunderstorms) can cause sufficient attenuation that the link will fail.

For the first 20 years of satellite communications, analog signals were widely used, with most links employing frequency modulation (FM). Wideband FM can operate at low carrier to noise ratios (CNRs), in the 5 to 10 dB range, but provides a signal to noise improvement so that video and telephone signals can be delivered with signal to noise ratios (SNRs) of 50 dB. The penalty for the SNR improvement is that the RF signal occupies a much larger bandwidth than the baseband signal. In satellite links that penalty results because signals are always weak and the improvement in SNR is essential. Analog satellite communications is now obsolete for commercial use, although US amateur radio enthusiast still use FM voice links with their OSCAR series of experimental satellites.

Almost all communication signals are now digital – telephony, data, DBS-TV, radio and television broadcasting, and navigation with GPS all use digital signaling techniques. However, sound radio still uses amplitude modulation (AM) and FM analog transmissions for the majority of terrestrial radio broadcasting because of the enormous numbers of existing radio sets. All of the LEO and MEO mobile communication systems are digital, taking advantage of voice compression techniques that allow a digital voice signal to be compressed into a bit stream at 4.8 kbps. Similarly, the Motion Pictures Expert Group developed the MPEG-2 and MPEG-4 video compression techniques allowing video signals to be transmitted in full fidelity at rates less than 4 Mbps.

The most profitable application of satellite communications to date has been broadcasting. One GEO satellite can broadcast its signals to an entire continent, North America and Europe being typical examples. The population of the United States in 2017 was estimated to be 332 million people, in approximately 110 million households. DirecTV and Dish network together had 33 million subscribers to their DBS-TV transmissions, or nearly one third of all households in the United States. That is why Figure 1.2 shows that distribution of television programming is by far the largest revenue earner worldwide. However, this may change in the next decade if the proposed constellations of thousands of LEO satellites providing worldwide internet access are successfully completed.

The constellation of 24 GPS satellites is designed to provide continuous navigation services to every part of the earth. This is another example of satellite broadcasting, this time from a medium earth orbit. The manufacture and sale of GPS receivers represent 19% of the worldwide revenue from satellite communications systems. By comparison, satellites that provide links between individual users, as illustrated in Figure 1.3b, have a much smaller number of users and do not have the earning power of broadcasting satellites unless a worldwide constellation of thousands of LEO satellites is constructed. User terminals for LEO satellites need phased array antennas to track the satellites across the sky, at a much lower price than any such antennas available before 2017. A target price for the phased array antenna of US$200 is needed to make LEO internet access terminals available to a worldwide customer base. The challenge for satellite internet access systems is to serve a sufficiently large user base at a data rate and price that is comparable to other internet providers.

1.5 Summary

Satellite communication systems have become an essential part of the world's telecommunications infrastructure, serving billions of people with video, data, internet access, telephone, and navigation services. Despite the growth of fiber optic links, which have much greater capacity than satellite systems and a lower cost per bit, satellite systems continue to thrive and investment in new systems continues. Satellite services have shifted away from telephony to video and data delivery, with television broadcasting directly to the home emerging as one of the most powerful applications. GEO satellites carried the majority of services in 2018, because the use of high gain fixed antennas at earth stations maximizes the capacity of the satellite. Over the years, there has been a trend away from trunk communications using very large earth station antennas toward delivery from more powerful satellites to individual users with much smaller antennas. VSAT networks using small antennas and low power transmitters are popular for linking together many locations in a single organization, such as retail stores and automobile dealerships. LEO and MEO satellites are used for mobile communications and navigation systems and, as the need for Geographic Information Systems grows with a variety of applications, LEO earth imaging satellites have the potential to provide strong revenue streams. Internet access by satellite is likely to be the largest sector of the industry by 2025.

1.6 Organization of This Book

Chapter 1 introduces the history of satellite communications and some of the ways that satellites are used.

Chapter 2 sets out the basics of satellite orbits and the factors that influence a satellite once in orbit. Calculation of look angles – where to look for a satellite in the sky – is restricted to GEO satellites. Software is needed to calculate look angles for LEO and MEO satellites as they move across the sky.

Chapter 3 describes the subsystems required to keep a communications satellite in orbit and functioning correctly. The communication system is covered in greater detail, including the organization of transponders, transmit and receive antennas, and use of frequency bands.

Chapter 4 covers the theory of radio communications and the calculation of carrier to noise ratio in a satellite link, and also low noise receiver design. The design of satellite links to achieve specific CNR values to maintain a particular error rate under conditions of atmospheric attenuation on the radio links is described in detail.

Chapter 5 concentrates on digital modulation methods and their performance in a satellite link. Forward error correction and error control methods used in DBS-TV and data links are discussed.

Chapter 6 covers multiple access techniques used in satellite communication systems to share the available resources of the satellite between multiple users. Frequency division multiple access, time division multiple access and code division multiple access (spread spectrum) are the main methods, with random access often used in the acquisition of a channel. Onboard processing and satellite switching techniques are discussed.

Chapter 7 explains the effect of the atmosphere on satellite-earth links, with rain being the most important. Techniques for the prediction of attenuation by clouds and rain are presented and methods for assessing the availability of satellite links are described. The RF frequency of a satellite link has a strong influence, as rain attenuation increases approximately as the square of frequency above 10 GHz.

Chapter 8 discusses some of the many low throughput applications for cubesats, mobile voice links, and VSAT networks. The commercial world of satellite communications is dominated by large geostationary satellites that can deliver tens or hundreds of gigabits per second, but there are many applications for small satellites with much lower throughput.

Chapter 9 describes the many orbits that are employed by satellite systems, generically grouped as non-geostationary (NGSO). These include LEO and MEO, which are becoming increasingly important for internet access via satellite.

Chapter 10 explains how direct broadcast satellite television and radio satellites provide hundreds of video and audio channels to subscribers. Techniques to mitigate the effect of rain on the RF path between the satellite and earth are described, and the probability of outages is discussed.

Chapter 11 is new to the third edition of *Satellite Communications*, covering the topic of internet access via satellite. This has become an important service for people in rural areas who are not served by cable companies or cellular telephone. Satellite internet access is also important in poorer countries where infrastructure is less well developed and satellite access can provide service over a wide area. Both GEO and LEO access systems are discussed and compared in terms of cost and capacity.

Chapter 12 covers satellite navigation systems, with emphasis on GPS. As discussed earlier in this chapter, GPS has become a major part of the satellite communications industry accounting for 19% of all revenue in 2016. The design of GPS receivers and the acquisition of GPS signals is covered in detail, and the system's vulnerability to jamming is discussed.

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